CAD-CAM milled versus rapidly prototyped (3D-printed) complete dentures: An in vitro evaluation of trueness

Kalberer, Nicole ; Mehl, Albert ; Schimmel, Martin ; Müller, Frauke ; Srinivasan, Murali

Abstract: STATEMENT OF PROBLEM Complete dentures fabricated by computer-aided design and computer-aided manufacturing (CAD-CAM) techniques have become popular. The 2 principal CAD-CAM techniques, milling and rapid prototyping (3D printing), used in the fabrication of complete dentures have been reported to yield clinically acceptable results. However, clinical trials or in vitro studies that evaluated the accuracy of the 2 manufacturing techniques are lacking. PURPOSE The purpose of this in vitro study was to compare the differences in trueness between the CAD-CAM milled and 3D-printed complete dentures. MATERIAL AND METHODS Two groups of identical maxillary complete dentures were fabricated. A 3D-printed denture group (3DPD) (n=10) and a milled denture group (MDG) (n=10) from a reference maxillary edentulous model. The intaglio surfaces of the fabricated complete dentures were scanned at baseline using a laboratory scanner. The complete dentures were then immersed in an artificial saliva solution for a period of 21 days, followed by a second scan (after immersion in saliva). A third scan (after the wet-dry cycle) was then made after 21 days, during which the complete dentures were maintained in the artificial saliva solution during the day and stored dry at night. A purpose-built 3D comparison software program was used to analyze the differences in the trueness of the complete dentures. The analyses were performed for the entire intaglio surface and specific regions of interest: posterior crest, palatal vault, posterior palatal seal area, tuberosity, anterior ridge, vestibular flange, and mid-palatal raphae. Independent t tests, ANOVA, and post hoc tests were used for statistical analyses (=.05). RESULTS The trueness of the milled prostheses was significantly better than that of the rapid prototyping group with regard to the entire intaglio surface (P<.001), posterior crest (P<.001), palatal vault (P<.001), posterior palatal seal area (P<.001), tuberosity (P<.001), anterior ridge (baseline: P<.001; after immersion in saliva: P=.001; after the wet-dry cycle: P=.011), vestibular flange (P<.001), and mid-palatal raphae (P<.001). CONCLUSIONS The CAD-CAM, milled complete dentures, under the present manufacturing standards, were superior to the rapidly prototyped complete dentures in terms of trueness of the intaglio surfaces. However, further research is needed on the biomechanical, clinical, and patient-centered outcome measures to determine the true superiority of one technique over the other with regard to fabricating complete dentures by CAD-CAM techniques.

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ABSTRACT (348/400)

Statement of problem Computer Aided Design/ Computer Aided Manufacturing (CAD/CAM) manufactured Complete Removable Dental Prostheses (CRDPs) have evolved exponentially in the last decade. The two principal CAD/CAM techniques, milling and rapid prototyping (3D-printing), employed in the fabrication of CRDPs have been reported to yield clinically acceptable results. However, the accuracy of the two manufacturing techniques has never been compared, either in bench experiments or by clinical trials.

Purpose This in vitro bench experiment aimed to compare the differences in trueness between the CAD/CAM milled CRDPs and rapidly prototyped (RP) CRDPs.

Material and Methods Two groups of identical maxillary CRDPs were manufactured (Group#1: RP: n=10; Group#2: Milled: n=10) from a reference maxillary edentulous model. The intaglio surfaces of the fabricated CRDPs were first scanned (BL) using a laboratory scanner. The CRDPs were then immersed in an artificial saliva solution for a period of 21 days, following which a second scan (PIS) was done. A third scan (WDC) was then made after 21 days, during which the CRDPs were maintained in the saliva solution during day and stored dry at night. A purpose-built 3D comparison software was used to analyze the differences in the trueness of the CRDPs. The analyses were performed for the entire intaglio surface, and specific regions of interest (posterior crest, palatal-vault, posterior palatal seal area (PPS), tuberosity, anterior-ridge, vestibular-flange and mid-palatal raphae). ANOVA and post-hoc tests were applied for statistical analyses (α=0.05).

Results The trueness of the milled prostheses was significantly better than that of the RP group with regards to the entire intaglio surface ($p<0.001$), posterior crest ($p<0.001$), palatal-vault ($p<0.001$), PPS ($p<0.001$), tuberosity ($p<0.001$), anterior-ridge (BL: $p<0.001$; PIS: $p=0.001$; WDC: $p=0.011$), vestibular-flange ($p<0.001$), and mid- palatal raphae ($p<0.001$).

Conclusion The CAD/CAM milled CRDPs, under the present manufacturing standards, are superior to the rapidly prototyped CRDPs in terms of trueness of the intaglio surfaces. However, further research is needed on a larger number of biomechanical, clinical and patient centered outcome measures, to evidence the true superiority of one technique over the other with regards to manufacturing CRDPs with CAD/CAM techniques, taking the rapidly evolving technical possibilities into account.

Clinical implications: This study provides evidence to help in the clinical decision making for choosing the appropriate CAD/CAM manufacturing technique for fabricating CRDPs. The study also provides sufficient information to encourage future research to clinically validate the findings of this bench experiment.

Introduction

The fabrication of complete removable dental prostheses (CRDPs) by computer aided designing and manufacturing (CAD/CAM) methods has witnessed a phenomenal rise, in both clinical and laboratory practices, during the recent years.[1] This gaining popularity may be attributed to the considerable improvements in the CAD/CAM techniques, the growing awareness amongst the dental practitioners and laboratory technicians along with an increasing flexibility to combine parts of the digital workflow with conventional clinical/laboratory protocols. To date, two established CAD/CAM techniques, either by a computerized numeric control (CNC) subtractive milling process or by a system of rapid prototyping (RP) commonly known as 3D printing, the latter being an additive manufacturing process are available to fabricate CAD/CAM CRDPs. Most manufacturers currently employ the milling technique for commercial production of CRDPs, while the RP method is mainly used for fabricating provisional or try-in CRDPs and, on a smaller scale, definitive CRDPs. Whereas the milling process implies the loss of large quantities of denture base material, the more recent 3D prototyping promises a more sustainable additive approach by using less denture resin.

CRDPs manufactured with either of the two CAD/CAM techniques have been documented. When compared to the conventional CRDPs, CAD/CAM milled CRDPs show similar or better fit of the intaglio surfaces, equal biocompatibility and improved mechanical properties.[2-7] High patient and clinician satisfaction have also been reported with CAD/CAM milled CRDPs.[8,9] The clinical protocols considerably reduce the chairside time, while the manufacturing process may reduce the laboratory fees in some countries.[10] CRDPs manufactured by RP technique have also elicited comparable patient satisfaction when compared to conventional CRDPs;[11,12] RP has been further used in CRDP fabrication for precise reproduction of denture bases and printed wax patterns.[13,14] Although both techniques

are successful in manufacturing clinically acceptable CRDPs, no study, till date, has actually compared the precision of the intaglio surface between the CRDPs manufactured by RP (3D printing) and a milled technique. This study aims to compare the trueness of the intaglio surfaces CRDPs manufactured by the CAD/CAM milling technique with those fabricated using the RP (3D printing) technology. Therefore, the null hypothesis set for this *in vitro* study was that there is no difference in the trueness of the intaglio surfaces of CRDPs manufactured either by CAD/CAM RP or milling techniques.

Materials and Methods

This *in vitro* study was conducted in the Division of Gerodontology and Removable Prosthodontics, University Clinics of Dental Medicine, University of Geneva, Switzerland. An ethical approval was not required for performing this study, because no patient records or data were used for this bench experiment. The color mapping and analysis of the differences were done at the Division of Computerized Restorative Dentistry, Clinic for Preventive Dentistry, Periodontology and Cariology, Center for Dental Medicine, University of Zurich, Switzerland.

Samples size

The sample size for the current study was calculated using the results from a previously published study.[3] The effect size (dz=1.5004) and the required sample size were calculated for α=0.05 and a power of 0.95 (1-β err prob), assuming a normal distribution. For this study, a sample size of 9 was obtained and subsequently increased to 10 per group, to remain consistent with previous similar published studies and to avoid errors.[2,3] The power analysis was performed using the freeware (G*Power for Mac OSX, Version 3.1.9.2, Düsseldorf, Germany).[15]

Master reference model

A completely edentulous maxillary cobalt-chrome model served as the master reference model for the current study. This model has been used in a previous experiment.[3] All the CRDP specimens used in this bench experiment were fabricated using the scan of this reference model.

Master reference scan

A master scan of the reference model was performed using a laboratory scanner (IScan D103i, Imetric 3D SA, Courgenay, Switzerland). The high-resolution scanner is calibrated to a precision of 6µm,[16] with a manufacturer specified nominal point spacing of 6–8µm with a repeatability of 10µm at an accuracy of 20µm. The bundle scanner software is equipped with an auto-align function that aligns multiple scan sets and the resultant information is stored in a 3D *.stl-format.

CRDPs CAD Design

The file of the master scan was exported in an electronic format (*.stl) to the CAD/CAM CRDP manufacturer using a purpose-built software (AvaDent™ Connect software, version 3.52, AvaDent™, Global Dental Science Europe BV, Tilburg, Netherlands). The anatomical landmarks were identified and the peripheral limits were marked on a virtual model in the AvaDent™ design software, which then served to design the final CRDP. A digital preview was generated and sent for approval to the investigators before manufacturing. Both, milled and 3D printed CRDPs used the same design.

Study groups

A total of 20 CRDPs were fabricated using the scan master reference model applying the two mentioned CAD/CAM manufacturing techniques (figure 1). Group 1 (n=10) comprised of CRDPs manufactured using the RP technique (NextDent B.V., Soesterberg, Netherlands), while group 2 consisted of 10 fully milled CRDPs (AvaDent™, Global Dental Science Europe BV, Tilburg, Netherlands).

Lubricant media

A liquid media was a custom-fabricated artificial saliva solution, manufactured solely for the purpose of these bench experiments; its composition has been described in detail in previously published studies.[3, 17, 18]

Entire intaglio surface and specific regions of interest (figure 2)

Based on clinical relevance for denture function, the entire intaglio surface and certain regions of interests were selected for analysis:

a. Posterior crest,
b. Palatal vault,
c. Posterior palatal seal area (PPS),
d. Anterior-ridge,
e. Tuberosities,
f. Vestibular-flange, and
g. Mid-palatal raphae (MPR).

Protocol

At first, the master reference model was scanned to form the master scan data file, which was used for the manufacturing of the CRDPs. This master scan was also used later for data analysis and comparison. After manufacturing, the specimens were quality-checked for any defects. At baseline (BL) the intaglio surfaces of the CRDPs specimens (n=20 specimens; Group 1: n=10, Group 2: n=10) were scanned. Subsequently the samples were incubated in an artificial saliva solution for a period of 21 days at room temperature. At the end of this period, a second scan of the intaglio surface was performed (post-immersion-scan; PIS). The following 21 days the specimens were immersed during the day in the artificial saliva solution and were stored dry during the night. The intaglio surface was then scanned a third and last time (wet/dry cycle; WDC).

Scan procedure and 3D comparison

All intaglio surfaces were scanned by a single investigator (NK), adhering to principles of extra-oral laboratory scanning procedures as recommended by the manufacturer, using the same aforesaid laboratory scanner. For comparative analyses a purpose-built 3D comparison software was used (Oracheck version 2.10, Cyfex, Switzerland). The scan file of the master reference model was inverted and, on which, the intaglio surface scans of all specimens were superimposed.[3,19] The software calculated the 3D ? distances between the superimposed matching points. Mean values and standard deviations were calculated for the entire intaglio surface as well as the regions of interest.

Statistical analysis

Normal distribution was confirmed before ANOVA and post hoc tests were used to demonstrate any significant differences between the groups with respect to the entire intaglio

surfaces and the specified regions of interests investigated. All statistical analyses were performed using the SPSS® software package (version 24.0. IBM® Corporation, Armonk, NY, USA).

Results

Trueness of the entire intaglio surface (Table 1, Figures 3 and 4)

Inter-group results *(Group#1 versus Group#2)*

At the given time-points, BL, PIS, and WDC, the trueness of the entire intaglio surface was significantly better in the CRDPs of group #2 than those of group #1 ($p<0.001$).

Intra-group results *(BL versus PIS; BL versus WDC; PIS versus WDC)*

Within group analysis revealed that there was a significant difference in the trueness of the entire intaglio surface in group#1 when compared between BL and PIS ($p<0.001$), BL and WDC ($p=0.003$), but not between PIS and WDC ($p=0.205$). Group#2 did not show any statistically significant differences in trueness between the 3 evaluated time points.

Trueness in the regions of interest (Table 1, Figures 3 and 4)

Inter-group results *(Group#1 versus Group#2)*

The trueness of the CRDPs in group #2 was significantly better at BL, PIS and after WDC, with regards to the posterior crest ($p<0.001$), the palatal-vault ($p<0.001$), PPS ($p<0.001$), the anterior-ridge (BL: $p<0.001$; PIS: $p=0.001$; WDC: $p=0.011$), the tuberosities ($p<0.001$), the vestibular-flange ($p<0.001$), and the MPR ($p<0.001$).

Intra-group results *(BL versus PIS; BL versus WDC; PIS versus WDC)*

In group#1, there was a significant difference for the PPS area when compared between BL and PIS ($p<0.001$) as well as between BL and WDC ($p=0.007$) but no difference between PIS and WDC ($p=0.261$). The trueness in PPS area, improved after the incubation in saliva.

No significant differences were observed in the trueness of the other investigated regions of interest for group#1.

Group#2 showed significant differences in the posterior crest (BL versus WDC: $p=0.020$), PPS area (BL versus WDC: $p=0.015$; PIS versus WDC: $p=0.023$), anterior-ridge (BL versus WDC: $p=0.037$), and in the MPR area (BL versus PIS: $p=0.010$; BL versus WDC: $p=0.045$).

Discussion

The fabrication of CRDPs by subtractive milling or by additive rapid prototyping are recent developments in the field of complete denture prosthodontics. Although, both techniques utilize a digital image file designed by a CAD software to manufacture the CRDPs, the two modes of fabrication however are entirely different from one another. In the milling method, the CRDP is fabricated by a milling station using a pre-polymerized polymethylmethacrylate (PMMA) puck manufactured under high pressure. While the RP technique uses photo-sensitive liquid resins, repetitively layered on a support structure and polymerized by an ultra-violet (UV) or a visible light source. Distinct advantages and disadvantages for each of the two techniques do exist. Manufacturing CRDPs from a pre-polymerized PMMA puck may be advantageous in eliminating ill-effects such as shrinkage and porosities, caused by the packing and polymerization process. Also, they possibly contain lower levels of residual monomer, and seem to afford superior material properties. The residual monomer content of the milled CRDPs was however, not markedly reduced when compared with conventional heat-polymerized CRDPs, but was observed to be significantly lower when compared to

CRDPs manufactured with auto-polymerizing resins.[6] These might be important factors to consider while comparing them with rapidly prototyped CRDPs. The RP technique uses uncured resins for manufacturing the CRDPs and once manufactured, it requires an additional final light-polymerization step to complete the curing process. During the RP workflow, polymerization shrinkage is theoretically possible as CRDPs are not completely polymerized before the final light polymerization procedure. A deformation of the prostheses can always occur when demounting the partially cured CRDP from the build platform, despite adequate care being exercised. Furthermore, a residual layer of uncured resin invariably remains on the finished prostheses, which has to be eliminated by thorough rinsing with a suitable solvent. On the flip side, the claimed advantages of an additive manufacturing process include higher accuracy, limiting material wastage, and low infrastructure costs, however, these have not yet been scientifically proven with regards to CRDP fabrication. Theoretically, solely on the basis of the different manufacturing processes, a logical difference in the accuracy of the fabricated CRDPs should exist, but both techniques have been documented to be clinically acceptable if not superior when compared to conventional methods.[2-13] The superiority, if existing, of one CAD/CAM technique over the other has not been investigated so far.

The results of this in vitro study demonstrate that the trueness of the CAD/CAM milled CRDPs was statistically better than the rapidly prototyped CRDPs both for the entire intaglio surface and the specific regions of interest. Therefore, the initially set null hypotheses is rejected by virtue of the findings of this study. Whether this difference in the trueness is clinically relevant remains debatable, as studies have demonstrated that the accuracy of rapidly prototyped CRDPs have clinically acceptable levels of precision and have also reported good patient and clinician satisfaction.[11-14] A further important aspect to consider is whether the rapidly prototyped CRDPs would be dimensionally stable over long-term given the fact that they are being manufactured using light-polymerizing resins, and no studies exist

in the current literature that elucidate on this aspect. Despite the inferior trueness in the present study, it seems worthwhile to invest in perfecting the RP techniques, as they present some substantial advantages to the CAD/CAM milling techniques. Sustainability and responsible use of our planets resources were stated a political priority by the United Nations. With a projected estimate of 61 million dentures to be made in 2020 for the US alone,[20] global numbers are expected to be exponentially higher. Therefore a substantial limitation of environmental pollution with plastic particles may be achieved, if judicious manufacturing techniques are adopted and may well further justify the developments of the RP techniques in a humanitarian aspect. Small 3D printers cost a fraction of a professional milling machine, and could possibly be afforded in those economically poor and non-industrialized parts of this world, where edentulism is most prevalent and skilled dental technicians are scarce. On-site manufacturing would also avoid shipping costs. In a long-term perspective, access to CRDPs may be extended to patient groups who are currently deprived of restorative oral health care.

Technical improvements in terms of trueness can be expected in the near future, as CAD/CAM techniques are developing very rapidly. But before recommending RP CRDP manufacturing as a standard manufacturing procedure, more research is needed. There are no studies on the monomer-based ester compounds that are used in rapid prototyping with regards to allergenic potentials, residual monomer levels, material and color stability, material compatibility to conventional relines, mechanical properties, and biocompatibility. The appearance of the two different denture types has to be studied as esthetics are of increasing importance in our modern society. Last but not least, patient centered outcome measures have to be considered.

Conclusions

The CADCAM milled CRDPs, under the present manufacturing standards, are superior to the rapidly prototyped CRDPs in terms of trueness of the intaglio surfaces. However, further research is needed on a larger number of biomechanical clinical and patient centered outcome measures, to evidence the true superiority of one technique over the other with regards to CRDPs.

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Table 1. Differences (mean ± standard deviations in microns) in trueness of the two groups of CRDPs showing inter-group and intra-group analyses with 95% confidence intervals and statistical significance set to p<0.05.				
Regions		**3D printed**	**Milled**	**p-value***
Total surface	BL	95.33±7.54	34.93±4.67	<0.001
	PIS	76.59±7.22	33.26±2.09	<0.001
	WDC	83.00±7.88	33.69±2.62	<0.001
	***p*-value§**	<0.001	0.515 (ns)	
Posterior crest	BL	58.11±12.84	32.53±2.50	<0.001
	PIS	47.64±7.97	36.03±2.15	<0.001
	WDC	47.80±5.47	36.65±4.31	<0.001
	***p*-value§**	0.026	0.014	
Palatal-vault	BL	64.36±9.05	17.73±2.94	<0.001
	PIS	59.98±7.21	15.97±0.82	<0.001
	WDC	64.46±13.26	17.02±1.44	<0.001
	***p*-value§**	0.538 (ns)	0.144 (ns)	
PPS area	BL	118.02±22.35	29.98±7.23	<0.001
	PIS	71.99±9.30	29.64±2.05	<0.001
	WDC	87.86±24.74	23.87±1.90	<0.001
	***p*-value§**	<0.001	0.008	
Tuberosity	BL	100.82±17.86	31.76±4.97	<0.001
	PIS	83.66±19.05	31.70±2.46	<0.001
	WDC	89.59±16.83	30.75±2.58	<0.001
	***p*-value§**	0.113 (ns)	0.775 (ns)	
Anterior-ridge	BL	43.27±7.07	32.74±2.25	<0.001
	PIS	42.04±4.93	34.12±3.68	0.001
	WDC	45.53±7.89	37.24±4.86	0.011
	***p*-value§**	0.510 (ns)	0.036	
Vestibular-flange	BL	76.23±10.71	41.90±6.40	<0.001
	PIS	72.70±8.68	39.83±4.47	<0.001
	WDC	80.65±17.04	38.74±3.30	<0.001
	***p*-value§**	0.385 (ns)	0.356 (ns)	
MPR	BL	95.27±9.24	22.81±3.14	<0.001
	PIS	87.47±13.86	19.93±0.73	<0.001
	WDC	86.70±11.53	20.48±1.28	<0.001
	***p*-value§**	0.212 (ns)	0.008	
CRDPs- complete removable dental prostheses; RP- rapidly prototyped, BL- baseline; PIS- post immersion in artificial saliva solution; WDC- wet/dry cycle; PPS- posterior palatal seal area; MPR- mid-palatal raphae; *- t-tests; §- ANOVA; ns- not significant.				

Table Legends

Table 1 — Differences (mean ± standard deviations in microns) in trueness of the two groups of CRDPs showing inter-group and intra-group analyses with 95% confidence intervals and statistical significance set to $p<0.05$.

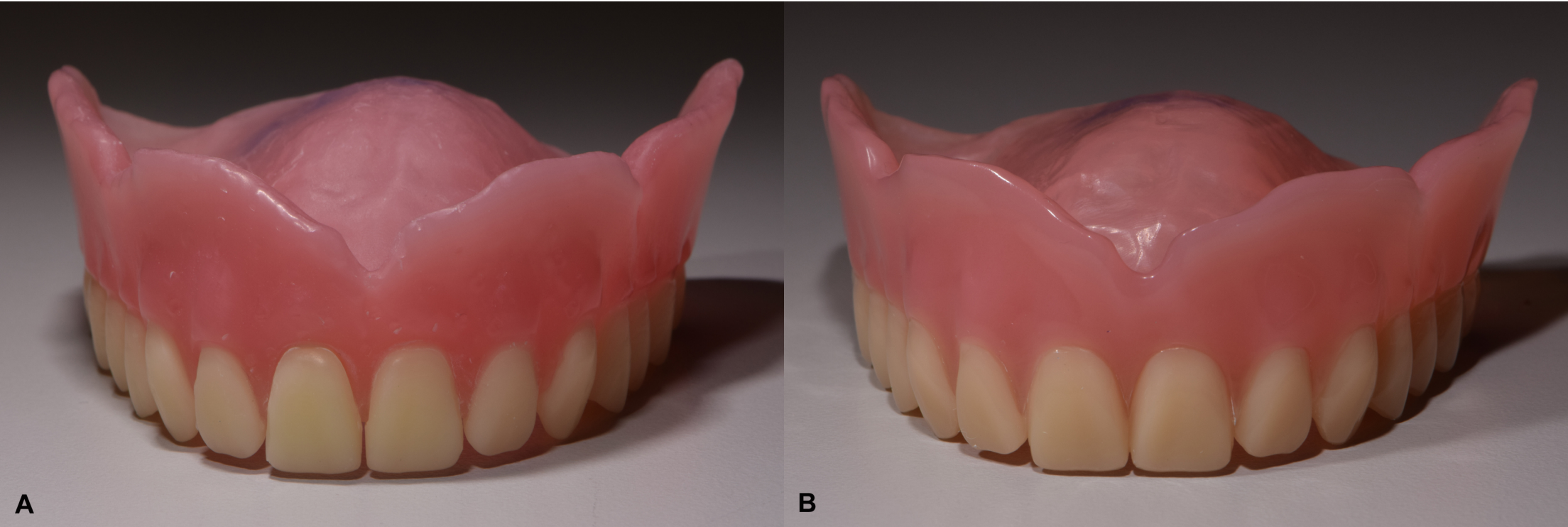
Figure Legends

Figure 1 — Example of a random sample from each of the two groups of CAD/CAM fabricated complete removable dental prostheses (CRDPs). A – Rapidly proto-typed (3D-Printed); B – Milled.

Figure 2 — The investigated specific regions of interests: (a) crest, (b) palatal vault, (c) posterior palatal seal area (PPS), (d) anterior ridge, (e) tuberosities, (f) vestibular flange, (g) mid-palatal raphae (MPR), (h) total intaglio surface.

Figure 3 — Color maps of the samples from group 1 at baseline (A), post-immersion in artificial saliva (B) and after a wet/dry simulation cycle (C) at a precision scale between -0.12 to 0.12 mm.

Figure 4 — Color maps of the samples from group 2 at baseline (A), post-immersion in artificial saliva (B) and after a wet/dry simulation cycle (C) at a precision scale between -0.12 to 0.12 mm.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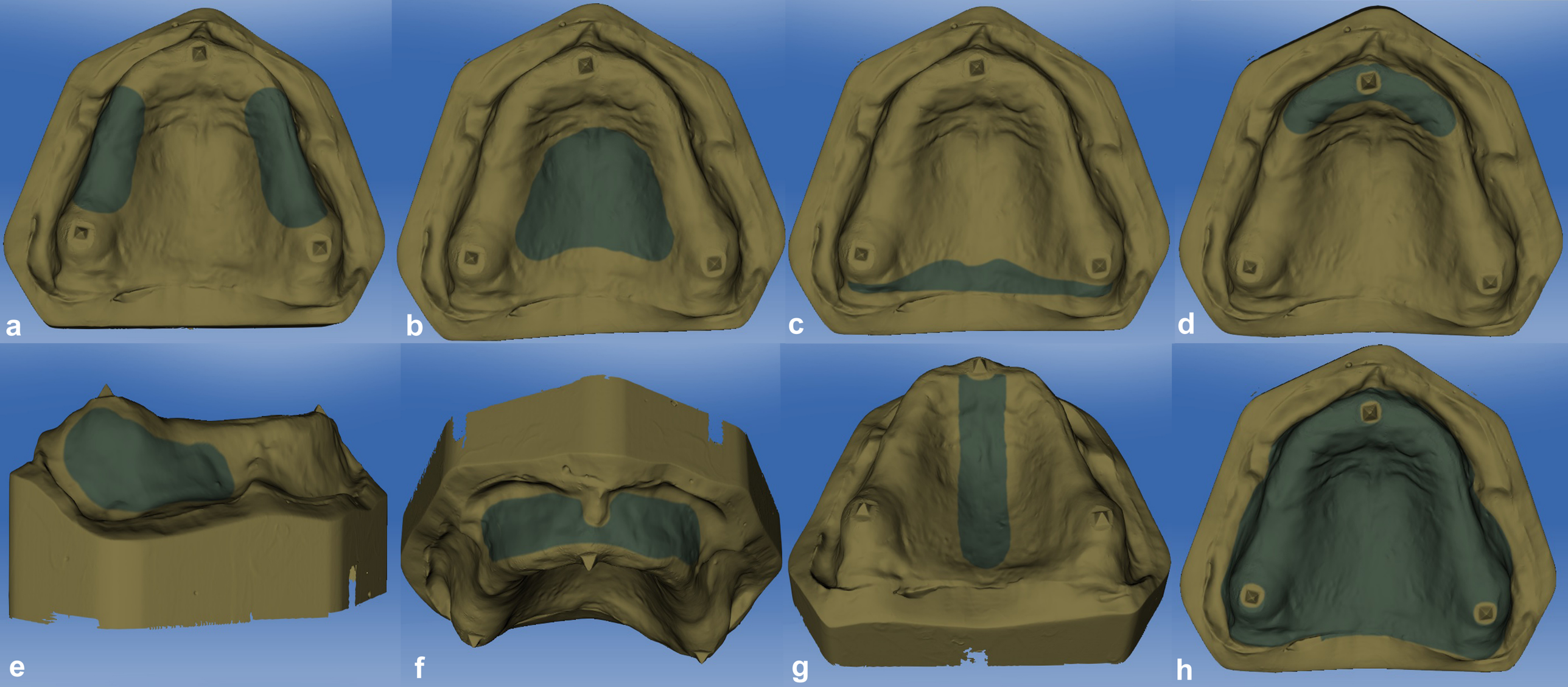
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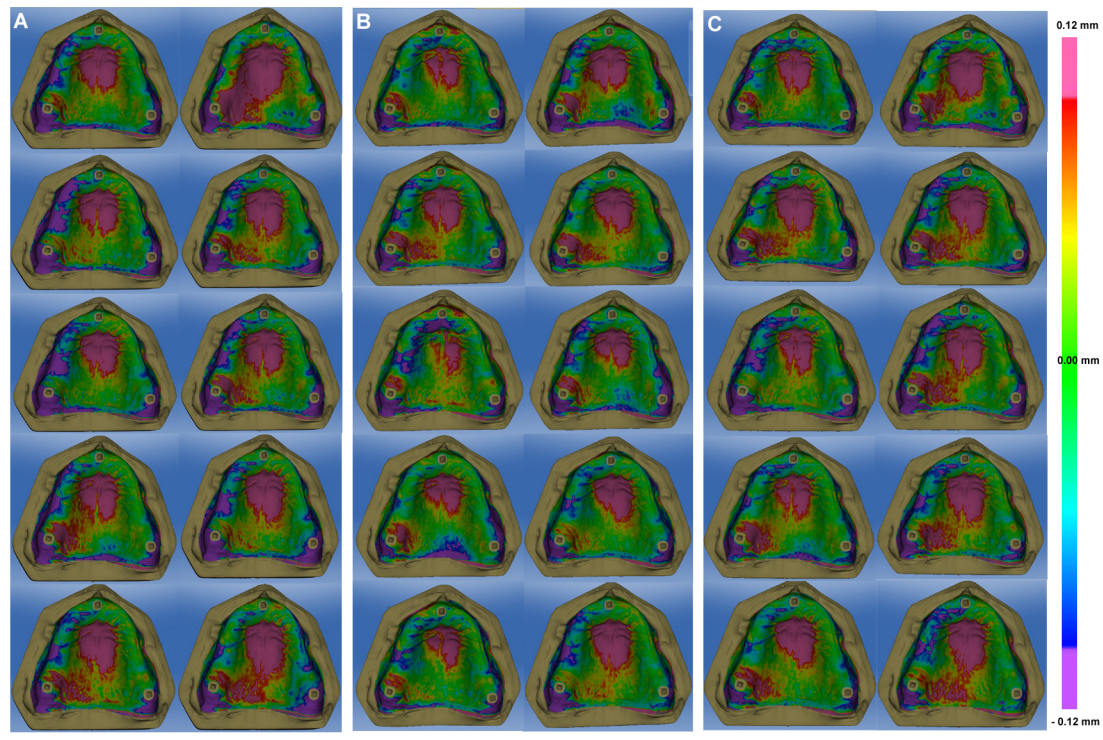
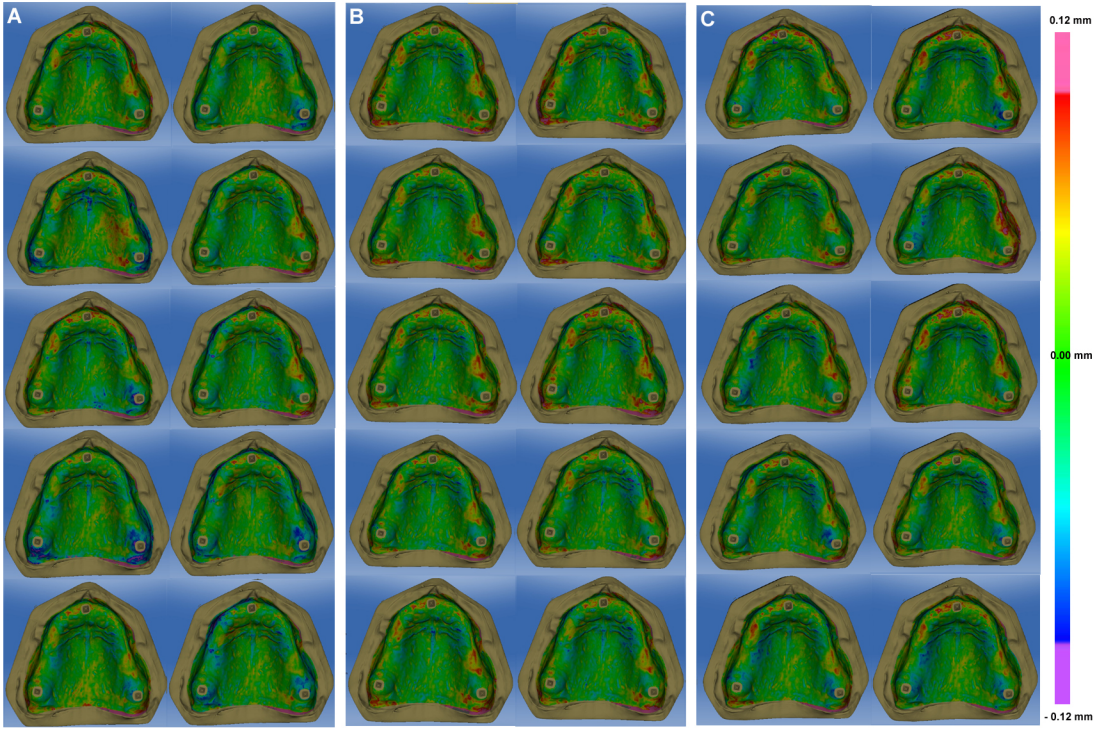

A
B
C
0.12 mm
0.00 mm
- 0.12 mm


A
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